

THERMINATOR: THERMal heavy-IoN generATOR[†]

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Abstract

THERMINATOR is a Monte Carlo event generator designed for studying of particle production in relativistic heavy-ion collisions performed at such experimental facilities as the SPS, RHIC, or LHC. The program implements *thermal models* of particle production with *single freeze-out*. It performs the following tasks: 1) generation of stable particles and unstable resonances at the chosen freeze-out hypersurface with the local phase-space density of particles given by the statistical distribution factors, 2) subsequent space-time evolution and decays of hadronic resonances in cascades, 3) calculation of the transverse-momentum spectra and numerous other observables related to the space-time evolution. The geometry of the freeze-out hypersurface and the collective velocity of expansion may be chosen from two successful models, the Cracow single-freeze-out model and the Blast-Wave model. All particles from the Particle Data Tables are used. The code is written in the object-oriented `c++` language and complies to the standards of the `ROOT` environment.

Submitted to Computer Physics Communications

[†] Work supported in part by the Polish State Committee for Scientific Research grant 2 P03B 059 25.

PROGRAM SUMMARY

Manuscript title: Therminator - THERMal heavy IoN generATOR

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Program title: THERMINATOR, April 2005, version 1.0;

RAM required to execute with typical data: 50 Mbytes

Number of processors used: 1

Computer(s) for which the program has been designed:

PC, Pentium III,IV, or Athlon, 512 MB RAM not hardware dependent;
(any computer with the `c++` compiler and the ROOT environment [1])

Operating system(s) for which the program has been designed:

Linux: Mandrake 9.0, Debian 3.0, SuSE 9.0, Red Hat FEDORA 3, *etc.*,
Windows XP with Cygwin ver. 1.5.13-1 and gcc ver. 3.3.3 (cygwin special);
– NOT SYSTEM DEPENDENT

External routines/libraries used:

ROOT ver. 4.02.00;

Programming language: `c++`

Size of the package: (324 KB directory 40 KB compressed distribution archive),
without the ROOT libraries (see <http://root.cern.ch> for details on the ROOT
[1] requirements). The output files created by the code need 1.1 GB for each
500 events.

Distribution format: tar gzip file

Number of lines in distributed program, including test data, etc.: 6516

Keywords: Monte Carlo generator, relativistic heavy-ion collisions, thermal
models, particle production, transverse-momentum spectra

PACS: 25.75.-q, 25.75.Dw, 25.75.Gz, 25.75.Ld

Nature of the physical problem:

Statistical models have proved to be very useful in the description of soft
physics in relativistic heavy-ion collisions [2]. In particular, with a few phys-

ical input parameters, such as the temperature, chemical potentials, and velocity of the collective flow, the models reproduce the observed particle abundances [3–15], the transverse-momentum spectra [16], balance functions [17, 18], or the elliptic flow [19, 20] in both non-strange and strange sectors. The key element of the approach is the inclusion of the complete list of hadronic resonances, which at the rather high temperature at freeze-out, ~ 165 MeV, contribute very significantly to the observed quantities. Their two- and three-body decays, taken from the tables, proceed in cascades, ultimately producing the stable particles observed in detectors. At the moment there exist several codes to compute the abundances of particles (the publicly available programs for this purpose are **SHARE** [21] and **THERMUS** [22]), which is a rather simple task, since the abundances are insensitive to the geometry of the fireball and its expansion. On the other hand, the calculation of the transverse-momentum spectra of particles is much more complicated due to the sensitivity to these phenomena. **THERMINATOR** deals with this problem, offering the *full information on the space-time positions and momenta of the produced particles*. As a result, the program allows to compute very efficiently the transverse-momentum spectra of identified particles and examine implications of the assumed expansion model. **THERMINATOR** allows easily for the departure from symmetries typically assumed in other approaches. This opens the possibility to study the dependence of physical quantities on rapidity and the azimuthal angle. The contribution of the resonances to various observables may be traced conveniently, and their role in the statistical approach may be verified. As a Monte Carlo event generator written in the object-oriented **c++** language in the **ROOT** [1] environment, **THERMINATOR** can be straightforwardly interfaced to the standard software routinely used in the data analysis for relativistic heavy-ion colliders, such as SPS, RHIC, and, in the future, LHC. In this way the inclusion of experimental acceptance, kinematic cuts, or interfacing with other programs poses no difficulty.

Method of solving the problem:

THERMINATOR uses the particle data tables [23] in the universal input form used by the **SHARE** [21] package. The user decides for the thermal parameters and the preferred expansion model. The optimum thermal parameters may be taken, *e.g.*, as those obtained with the help of **SHARE** [21] or **THERMUS** [22]. At the moment there are two different expansion models implemented in the code: the model of Ref. [16], based on the so-called Buda-Lund [24] parameterization, and the Blast-Wave model [25, 26]. The positions and velocities

of the particles are randomly generated on the hypersurface according to the statistical (Bose-Einstein or Fermi-Dirac) distribution factors. All particles, stable and unstable, are included. The particles move along classical trajectories from their initial positions, with velocities composed of the thermal motion and the collective expansion of the system. Stable particles just stream freely, while the resonances decay after some (randomly generated) time, which is controlled by the particle's lifetime. The decays are two-body or three-body, and their implementation involves simple kinematic formulas. The decays can proceed in cascades, down to the stage where only stable particles are present. All particles have tags indicating their parent. The secondary rescatterings are not considered in this approach. Full history of the event is stored in an output file, allowing for a detailed examination of the space-time evolutions and the calculation of the transverse-momentum spectra.

Purpose:

The ongoing analyses of the SPS and the RHIC data as well as the future heavy-ion program at LHC will certainly benefit from **THERMINATOR** as a tool for generating events in a simple statistical model. The Monte Carlo code written in `c++` and using the standard **ROOT** [1] environment can be easily adapted to purposes directly linked to experimental data analyses. The space-time tracking capability will allow, in the framework of the statistical approach, to better understand the physics of relativistic heavy-ion collisions. **THERMINATOR** calculates the particle spectra and other observables related to the space-time evolution of the system. It provides a `c++` framework which may be easily developed for detailed analyses of more involved observables such as, *e.g.*, correlation functions or HBT radii.

Computation time survey and storage requirements:

The generation of 500 events from scratch takes about 1 hour 15 minutes on a PC with Athlon-Barthon 2.5 GHz under Red Hat Fedora 3. Each subsequent 500 events take about 1 hour. To store 500 events about 1.1 GB disk storage is needed, depending on the kinematic range. After converting the output to the **ROOT** TTree format, 900 MB may be freed.

Accessibility:

<http://hirg.if.pw.edu.pl/en/therminator>

1 Introduction

Statistical description of heavy-ion experiments has proven to be very successful in understanding and quantitatively describing the *soft* physics, *i.e.*, the regime with transverse-momentum scales not exceeding, say, 2 GeV. The simple basic assumption that the hadronic matter reaches thermal equilibrium and undergoes rapid expansion [27–30] leads to a remarkably good description of the ratios of particle abundances measured in heavy-ion experiments, in particular at the high energies of the SPS ($\sqrt{s_{NN}}=8\text{--}17$ GeV) and RHIC (reaching $\sqrt{s_{NN}}=200$ GeV). The results for abundances may be found in [3–15]. Other details of different statistical approaches may be found in [24–26, 31–37].

Crucial for the success of the statistical approach is the complete inclusion of hadronic resonances, whose number grows rapidly according to the Hagedorn hypothesis [30, 38–42]. Numerous programs exist to analyze the ratios of particle abundances, with **SHARE** [21] and **THERMUS** [22] publicly available. The abundances are observables that are sensitive to the thermal parameters of the fireball created in the collision: temperature, chemical potentials, and fugacity factors. The abundances are basically insensitive to the expansion¹, which means that it only matters how many particles are formed and it is irrelevant how fast they move.

The situation is different for the description of the momentum spectra, where the collective motion of the expansion adds up to the thermal one generated in the local element of the fireball. Thus, the spectra are sensitive not only to the thermal parameters, but also to the geometry of the fireball and velocity of expansion. Surprisingly, very simple hypotheses for the geometry and expansion [16] allow for a good description of the RHIC data for the transverse-momentum spectra of identified particles, both in the non-strange and strange sectors [43]. The approach of Ref. [16] is based on the simplifying assumption that the so-called chemical and thermal freeze-out occur simultaneously thus we deal with a *single-freeze-out model*. Similar hypothesis is otherwise known as the *sudden hadronization* [44]. We follow this paradigm in **THERMINATOR** and throughout this paper².

¹Some dependence may come for boost non-invariant systems from the detector acceptance, however in the most studied mid-rapidity region at RHIC and at SPS this is a tiny effect.

²Since the program is an event generator, it would not be very complicated to add an “afterburner” that would scatter the particles elastically after they have frozen chemically,

THERMINATOR computes the transverse-momentum spectra of identified particles in the single-freeze-out model. The user has an option of choosing two variants of the geometry/expansion models: the Buda-Lund type expansion [24, 33] and the Blast-Wave type expansion [25, 26] (both models of expansion were used with a similar success in the original single-freeze-out model [16]). Other expansion models may be looked at with the need of only minor modifications to the code. As already mentioned, the key ingredient in the thermal approach are the hadronic resonances, which must be included in a complete way, together with their decay channels and branching ratios. **THERMINATOR** uses the same universal input files with the information from the Particle Data Tables [23] as the **SHARE** package [21] co-authored by two of us (WB, WF). The basic functionality of **THERMINATOR** is the calculation of the momentum spectra and, correspondingly, the analysis of the geometry and expansion. It allows for the optimum determination of the transverse flow in the assumed model of expansion. This may be very useful for SPS, RHIC, and the future heavy-ion program at LHC. However, the program is a versatile Monte Carlo event generator, and as such it may be used with slight modifications to analyze other observables, such as HBT correlation radii [33, 45–48], correlations of non-identical particles, or balance functions. With simple modifications amounting to a departure from the presently-implemented boost and azimuthal symmetries, one may look at the dependence of parameters and observables on rapidity, or at measures of the azimuthal asymmetry, such as the coefficient of the elliptic flow v_2 . We want to emphasize that **THERMINATOR** uses the **ROOT** environment, thus it may be conveniently linked to the standard software used for the data analysis.

2 Basics of the single-freeze-out model

The basic assumptions of the single-freeze-out model are as follows (for a detailed discussion see Refs. [16, 37, 43]):

1. At some point of the space-time evolution of the fireball the local thermal and chemical equilibrium is reached. The local particle phase-space densities follow the Fermi-Dirac or Bose-Einstein statistical distributions.

thus differentiating between the two freeze-outs.

2. Freeze-out occurs at universal values of the thermodynamic parameters. We have temperature T and three chemical potentials: baryon, μ_B , strange, μ_S , and related to the third component of isospin, μ_{I_3} . Typically, the potentials μ_S and μ_{I_3} are set from the condition of the overall strangeness neutrality and from the assumption that the ratio of the electric to baryon charge density equals the initial ratio, Z/A , where Z and A are the atomic and mass numbers of the colliding nuclei. The values of the thermodynamic parameters are obtained from fits to the measured ratios of the particle abundances. The publicly-available SHARE [21] or THERMUS [22] codes may be used here.
3. The freeze-out occurs on a boost-invariant cylindrically symmetric hypersurface, discussed in detail below. The velocity field of expansion is chosen appropriately, providing the longitudinal and transverse flow to the system. The particles generated at freeze-out are termed *primordial*.
4. The later evolution consists of decays of resonances which may proceed in cascades. All resonances from the Particle Data Tables [23] are incorporated.

The basic physics of the model is depicted in Fig. 1. The popular choices of the hypersurface of freeze-out and the velocity field of expansion are discussed in detail in Ref. [49]. The boost-invariant formalism has been developed by Schnedermann, Sollfrank, and Heinz [25]. The ansatz for the boost-invariant, cylindrically symmetric freeze-out hypersurface has the form

$$x^\mu = (t, x, y, z) = (\tilde{\tau}(\zeta) \cosh \alpha_\parallel, \rho(\zeta) \cos \phi, \rho(\zeta) \sin \phi, \tilde{\tau}(\zeta) \sinh \alpha_\parallel). \quad (1)$$

The parameter α_\parallel is the space-time rapidity. The boost-invariant freeze-out hypersurface is completely defined by the freeze-out curve parameterized by ζ . This curve defines the freeze-out times of the cylindrical shells with the radius ρ . The volume element of the freeze-out hypersurface is obtained from the equation

$$d^3\Sigma_\mu = \varepsilon_{\mu\alpha\beta\gamma} \frac{dx^\alpha}{d\alpha} \frac{dx^\beta}{d\beta} \frac{dx^\gamma}{d\gamma} d\alpha d\beta d\gamma, \quad (2)$$

which with the parameterization (1) yields

$$d^3\Sigma^\mu = \left(\frac{d\rho}{d\zeta} \cosh \alpha_\parallel, \frac{d\tilde{\tau}}{d\zeta} \cos \phi, \frac{d\tilde{\tau}}{d\zeta} \sin \phi, \frac{d\rho}{d\zeta} \sinh \alpha_\parallel \right) \rho(\zeta) \tilde{\tau}(\zeta) d\zeta d\alpha_\parallel d\phi. \quad (3)$$

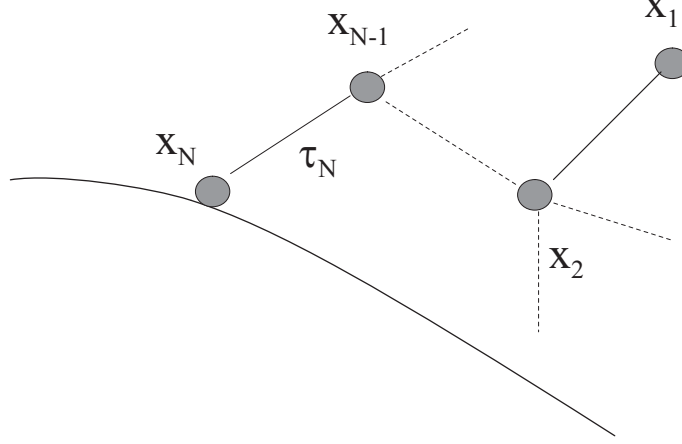


Figure 1: The cascade decay in the single-freeze-out model. An unstable particle is formed at some position on the hypersurface with the momentum composed of the thermal motion and the flow of the medium. Then the particle travels for some time depending on its lifetime and decays. The products, if resonances themselves, may decay further, until the stable particles are formed.

Similarly to Eq. (1) the boost-invariant four-velocity field has the structure

$$u^\mu = \cosh \alpha_\perp(\zeta) (\cosh \alpha_\parallel, \tanh \alpha_\perp(\zeta) \cos \phi, \tanh \alpha_\perp(\zeta) \sin \phi, \sinh \alpha_\parallel). \quad (4)$$

We note that the longitudinal flow is $v_z = \tanh \alpha_\parallel = z/t$ (as in the one-dimensional Bjorken model [50]), while the transverse flow at $z = 0$ has the form $v_r = \tanh \alpha_\perp(\zeta)$.

With the standard parameterization of the particle four-momentum in terms of rapidity y , azimuthal angle φ , and the transverse mass m_\perp ,

$$p^\mu = (m_\perp \cosh y, p_\perp \cos \varphi, p_\perp \sin \varphi, m_\perp \sinh y), \quad (5)$$

we find

$$p \cdot u = m_\perp \cosh(\alpha_\perp) \cosh(\alpha_\parallel - y) - p_\perp \sinh(\alpha_\perp) \cos(\phi - \varphi), \quad (6)$$

and

$$d^3\Sigma \cdot p = \left[m_\perp \cosh(y - \alpha_\parallel) \frac{d\rho}{d\zeta} - p_\perp \cos(\phi - \varphi) \frac{d\tilde{\tau}}{d\zeta} \right] \rho(\zeta) \tilde{\tau}(\zeta) d\zeta d\alpha_\parallel d\phi. \quad (7)$$

The Cooper-Frye [51] formalism yields the following expression for the momentum density of a given species of particles

$$\begin{aligned}
\frac{dN}{dyd^2p_\perp} &= \frac{1}{(2\pi)^3} \int_0^{2\pi} d\phi \int_{-\infty}^{\infty} d\alpha_\parallel \int_0^1 d\zeta \rho(\zeta) \tilde{\tau}(\zeta) \\
&\times \left[m_\perp \cosh(\alpha_\parallel - y) \frac{d\rho}{d\zeta} - p_\perp \cos(\phi - \varphi) \frac{d\tilde{\tau}}{d\zeta} \right] \\
&\times \left\{ \exp \left[\beta m_\perp \cosh(\alpha_\perp(\zeta)) \cosh(\alpha_\parallel - y) - \right. \right. \\
&\quad \left. \left. \beta p_\perp \sinh(\alpha_\perp(\zeta)) \cos(\phi - \varphi) - \beta \mu \right] \pm 1 \right\}^{-1}, \quad (8)
\end{aligned}$$

where $\beta = 1/T$ and $\mu = B\mu_B + S\mu_S + I_3\mu_{I_3}$. The expression in curly brackets is the Bose-Einstein or Fermi-Dirac distribution, with the corresponding minus or plus signs. **THERMINATOR** implements two models of the freeze-out hypersurface and velocity field, described in the following subsections.

2.1 The Cracow single-freeze-out model

We term the model [16], that has been used very successfully in the description of the RHIC data, the Cracow single-freeze-out model. It is defined by the equations

$$\tilde{\tau} = \tau \cosh(\alpha_\perp), \quad \rho = \tau \sinh(\alpha_\perp), \quad \tau = \text{const.} \quad (9)$$

and $u^\mu = x^\mu/\tau$. This parameterization yields the following distribution of the primordial particles

$$\begin{aligned}
\frac{dN}{dyd\varphi p_\perp dp_\perp d\alpha_\parallel d\phi d\rho} &= \frac{1}{(2\pi)^3} \left[m_\perp \sqrt{\tau^2 + \rho^2} \cosh(\alpha_\parallel - y) - p_\perp \rho \cos(\phi - \varphi) \right] \\
&\times \left\{ \exp \left[\beta m_\perp \sqrt{1 + \frac{\rho^2}{\tau^2}} \cosh(\alpha_\parallel - y) - \beta p_\perp \frac{\rho}{\tau} \cos(\phi - \varphi) - \beta \mu \right] \pm 1 \right\}^{-1}. \quad (10)
\end{aligned}$$

The variable ρ is limited from above by the maximum transverse size ρ_{max} .

2.2 Blast-Wave model

The other considered model of the fire-ball expansion is the Blast-Wave model³. In this case one specifies the freeze-out hypersurface and the velocity profile of the flow by the conditions:

$$\tilde{\tau} = \tau = \text{const}, \quad v_r = \tanh\alpha_\perp(\zeta) = \text{const}. \quad (11)$$

Then Eq. (8) takes the form

$$\begin{aligned} \frac{dN}{dyd\varphi p_\perp dp_\perp d\alpha_\parallel d\phi d\rho} &= \frac{\tau}{(2\pi)^3} m_\perp \cosh(\alpha_\parallel - y) \\ &\times \left\{ \exp \left[\frac{\beta m_\perp}{\sqrt{1-v_r^2}} \cosh(\alpha_\parallel - y) - \frac{\beta p_\perp v_r}{\sqrt{1-v_r^2}} \cos(\phi - \varphi) - \beta\mu \right] \pm 1 \right\}^{-1}. \end{aligned} \quad (12)$$

Again, the variable ρ is limited from above by the maximum transverse size ρ_{max} .

2.3 Decays of resonances

We incorporate all the four-**** and three-*** resonances. Following the scheme implemented in **SHARE** [21] we exclude all single-* resonances, and practically all double-** resonances listed in the Particle Data Tables [23]. The reader may use his preferences by modifying the input files. The stable particles and resonances are populated according to the formulas (10) or (12). All particles have their positions and momenta specified. Then, each resonance decays after some time, controlled by its lifetime $1/\Gamma$. In the rest frame of the resonance the decay at time τ occurs with the probability density $\Gamma \exp(-\Gamma\tau)$. The decays are two-body or three-body, and the physical values of the branching ratios are taken from the Particle Data Tables. Heavy resonances may decay in cascades. The kinematics of the decay is implemented in the rest frame of the decaying particle, and then the system is boosted to the reference frame in which the freeze-out hypersurface of Eqs. (10) and (12) is defined. For collisions of symmetric nuclei at RHIC it corresponds to the center-of-mass (CMS) frame.

³We should stress that the meaning of the blast-wave model here is different from the popular usage in fits to the heavy-ion data, since *we include the decays of resonances*.

The particles are distinguished by isospin, hence the branching ratios for strong decays incorporate the isospin Clebsch-Gordan factors. The method of computing the branching ratios, the policy of assigning the branching ratios to channels labeled as *seen* or *dominant*, and other details concerning the decays of particles are incorporated in the same fashion as in **SHARE** [21] where the reader is referred to for more details.

3 Description of THERMINATOR

THERMINATOR is written in **c++** and uses **ROOT** – *An object-oriented data analysis framework* [1]. A more sophisticated usage of **THERMINATOR** at the level of analysing the output requires a basic knowledge of **ROOT** from the user.

The block structure of **THERMINATOR** is shown in Fig. 2. Information on particle properties as well as the **THERMINATOR** parameters are read from the (modifiable) input files. Two programs, **term_events** and **term_tree** generate a **ROOT** tree which can be used within **ROOT** to generate physical results. The blocks of Fig. 2 are described in detail in the following.

3.1 Particle data files (**particles.data** and **decays.data**)

The structure of input files containing the information on the particle properties and their decays is the same as in **SHARE** [21], where the reader is referred to for a more detailed description. Here we just give the basic information.

The input file **particles.data** contains the information on the properties of particles such as mass, width, spin, isospin, the quark contents, and the Monte Carlo identification number. The file has the following format:

```
name mass width spin I I3 q s aq as c ac MC
```

where:

name the particle label used in the program,
mass mass in GeV,
width width in GeV,
spin spin,
I isospin,
I3 3rd component of isospin,
q, s number of light/strange quarks,

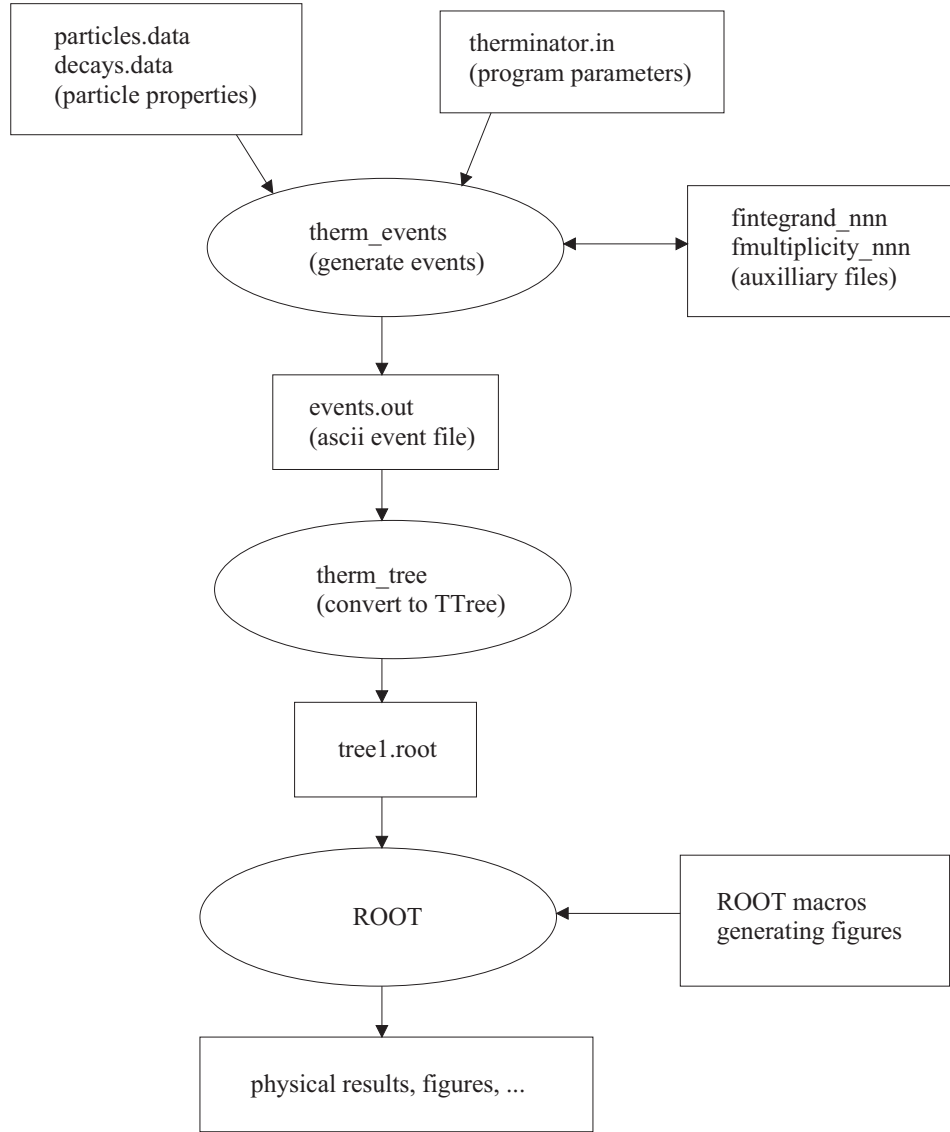


Figure 2: The block structure of THERMINATOR.

aq, as number of light/strange antiquarks,
c, ac number of charm/anticharm quarks,
MC particle's identification number, where available corresponding to the standard Monte Carlo particle identification convention [23].

The file `decays.data` contains the information on particle decays in the format:

Name_{parent} **Name**_{daughter1} **Name**_{daughter2} **Name**_{daughter3}⁴ **BR** **C–G?**(0/1)

where **BR** denotes the branching ratio of the decay and **C–G** refers to whether the branching ratio should be multiplied by a Clebsch–Gordan coefficients (**0**: no, **1**: yes). Normally, we use **1** for the two-body decays and **0** for the three-body decays, where the full (isospin-dependent) branching ratio BR is provided. The entry BR may be used to control the feed-down from the weak decays, in particular setting it to 0 would switch off the decay channel.

3.2 Input parameter file (`therminator.in`)

The execution of the THERMINATOR program is mainly controlled by the parameter input file, whose default name is `therminator.in`. Different parameter filename can be specified by the user at the command line as a parameter to the program. The file contains the following information, which must be filled by the user:

- NumberOfEvents** – the number of events to be generated (default: 500),
- Randomize** – if set to 1, the random number generator seed is initialized with the help of the current time, producing different seeds for every run of the program; if set to 0 the seeds (and therefore all the results) will be the same for each run of the program (default: 1),
- InputDirSHARE** – location of the SHARE input files (default: `../share`),
- EventOutputFile** – name of the ASCII file containing the generated events (default: `event.out`),
- FreezeOutModel** – selects the version of the freeze-out model used, the “Cracow” model (see Sect. 2.1) (value: `SingleFreezeOut`) as well as “BlastWave” model (see Sect. 2.2) (value: `BlastWaveVT`) are available (default: `SingleFreezeOut`),
- BWVt** – a parameter specific to the Blast-Wave model - the common velocity (default: 0.55) (v_r from (12)),
- Tau, RhoMax** – geometric parameters in units of fm (default: 9.74, 7.74) (τ from (10) or (12) and ρ_{max} from Sec. 2.1 or 2.2),

⁴Appears for the three-body decays only.

Temperature, MiuI, MiuS, MiuB – thermodynamic parameters in units of GeV (default: 0.1656, -0.0009, 0.0069, 0.0285) (T from (10) or (12) and μ_{I_3} , μ_B , and μ_S from Sec. 2),

AlphaRange, RapidityRange – integration ranges for longitudinal variables (space-time rapidity and rapidity) (default: 8.0 (-4.0, 4.0), 4.0 (-2.0,2.0)) (α_{\parallel} and y from (10) or (12)),

NumberOfIntegrateSamples – number of samples used in the determination of multiplicity and maximum of the integrand (default: 1000000).

The parameter file is properly commented for the ease of use.

3.3 Generation of the particle distribution

The generation of particle distributions proceeds in three main steps, two of which are performed only once per given parameter set.

In order to generate particles through a Monte Carlo method, the maximum value of the distributions on the right-hand-side of Eq. (10) or (12) must be known. It is found through a simple numerical procedure. A sample of particles is generated and the values of the distributions are calculated for each of them. The maximum value obtained is taken as the maximum of the requested distribution for the considered particle type. The authors have checked, by studying the resulting distributions, that if the size of the sample is large enough, the method provides a good estimate of the maximum value. The maximum value depends, in principle, on the particle type and values of parameters, but does not change from event to event. Therefore the value is calculated once for each particle type and stored in the file `fintegrandmax_nnn`, where `nnn` stands for a unique identifier for a given parameter set. Subsequent generations of events with the same parameters do not require the regeneration of the maximum values; they are read from the `fintegrandmax_nnn` file instead. This way the computation time is saved.

In order to generate events, a multiplicity of each particle type must be known. The average multiplicity per event can be calculated in a straightforward manner by numerically integrating the distribution functions in the given integration ranges (determined by the model parameters). This procedure must also be done only once per parameter set. The average multiplicity of each particle is stored in the working directory in a file named `fmultiplicity_nnn`, where `nnn` is the same unique identifier, as the one

used for the maxima discussed above. The multiplicities are then read in by subsequent generations, saving the time of calculation.

In the next step the program proceeds to its ultimate goal of generating events, *i.e.*, the data sets containing full information about produced particles, the history of their evolution, resonance decays, *etc.* Each event is generated separately. First, the multiplicities of each particle type are generated as random numbers from a Poissonian distribution, with the mean being the average particle multiplicity determined earlier. Then the program proceeds to generate particles, sequentially from the heaviest to the lightest particle type. The procedure is, in essence, the generation of the set of six random numbers (the magnitude of the transverse momentum p_T , the azimuthal angle of the transverse momentum φ , the rapidity y associated with the particle's momentum, the space-time rapidity α_{\parallel} associated with the particle's location, the transverse distance of the particle ρ , the azimuthal angle of the particle's location ϕ), distributed according to the formulae (10) or (12), depending on the selected source model. The integration ranges are determined by the model parameters and the user's input. The event generation procedure is a standard von Neumann method of rejection/acceptance of the given set of numbers based on the randomly generated test value distributed uniformly between 0 and f_{\max} , where f_{\max} is the maximum value of the distribution determined earlier. The accepted sets of numbers are stored in memory as representing the actual particles. The procedure ends when the determined number of particles of each particle type is generated. At this point all the *primordial* particles, stable and resonances, have been generated and stored in the event.

3.4 Implementation of two-body decays

The next step in the event generation is the simulation of the decays of unstable particles. A particle is treated as unstable if it has non-zero width in the `particles.data` input file. If the user wishes to prevent a decay of a particular resonance, he should modify the input file and set the width of a given particle to 0. Alternatively, decay channels may be switched-off selectively by setting the corresponding branching ratio in `decays.data` to zero.

The decays proceed sequentially from the heaviest to the lightest particle. The decay daughters are immediately added to the set of particles in the current event, hence they may decay in the subsequent steps. Most particles

have several decay channels. In each decay one of them is selected randomly with appropriate probability corresponding to the branching ratio from the `decays.data` input file. It may happen that the selected decay channel is of a sub-threshold type (average mass of the parent particle is smaller than the sum of masses of the daughter particles), which is not yet implemented in **THERMINATOR**. In such a case, the particle does not decay and the program proceeds to the next particle.

The selected decay channel can be two- or three-body. Both are implemented in **THERMINATOR** and treated on equal footing. We turn now to the discussion of the two-body decays; the specifics of the three-body decays are described in the next subsection.

First the lifetime $\Delta\tau$ of the decaying particle of mass M , moving with the four-momentum p^μ , is generated randomly according to the exponential decay law, $\exp(-\Gamma\Delta\tau)$. Once the lifetime $\Delta\tau$ of the particle is known, the space-time point of its decay can be calculated, by taking its original space-time position x_{origin}^μ (determined from the values τ , ρ , α_\parallel , and ϕ), and adding to it the space-time distance traveled by the particle,

$$x_{\text{decay}}^\mu = x_{\text{origin}}^\mu + \frac{p^\mu}{M}\Delta\tau. \quad (13)$$

This calculation is always done in the CMS reference frame of the colliding system in the Cartesian coordinates. Note that Eq. (13) guarantees that the space-time interval between the origin and decay point is equal to $\Delta\tau$.

The energies E_1 , E_2 , and the three-momenta \mathbf{p}_1 , \mathbf{p}_2 of the daughter particles are initially determined in the rest frame of the parent particle from the energy-momentum conservation laws, which yield:

$$E_{1,2} = \frac{M^2 - m_{2,1}^2 + m_{1,2}^2}{2M}, \quad (14)$$

$$|\mathbf{p}_1| = |\mathbf{p}_2| = \frac{[(M^2 - (m_1 + m_2)^2)(M^2 - (m_1 - m_2)^2)]^{1/2}}{2M}. \quad (15)$$

Here m_1 , m_2 are the masses of the daughter particles. The direction of the three-momentum of particle 1 is generated randomly and is evenly distributed on the sphere in the parent particle's rest frame. The direction of the three-momentum of particle 2 follows from the momentum conservation. Having generated the decay momenta of both particles in the resonance rest frame, we next boost them to the CMS frame with the parent particle velocity. The

decay point of the parent particle (13) is taken as the origin of the daughter particles.

Together with each daughter particle the reference to the parent particle is stored. This enables the full tracing of the cascade decay tree in the analysis of the **THERMINATOR** output. Also, the parent particle is flagged as “decayed” which is later indicated in the output file.

3.5 Implementation of three-body decays

Following the common practice, we assume that the transition amplitude in three-body decays is constant, *i.e.*, not dependent on the momenta. Similarly to the case of two-body decays, the momenta of the emitted particles are first determined in the parent particle’s rest-frame and only at the end are boosted to the CMS frame with the parent velocity. The three-momenta of daughter particles considered in the parent particle rest frame lie all in one plane. Moreover, the energy distributions of the daughter particles in three-body decays with constant matrix element are uniform (see for example Ref. [52]), therefore we may generate randomly the energies E_2 and E_3 of the daughter particles 2 and 3 in the energy range allowed by the energy conservation: $m_2 \leq E_2 \leq M - m_1 - m_3, m_3 \leq E_3 \leq M - m_1 - m_2$. The energy of the daughter particle 1 as well as the magnitudes of all three-momenta ($|\mathbf{p}_1|$, $|\mathbf{p}_2|$, and $|\mathbf{p}_3|$) follow from the energy and momentum conservation laws, which in addition determine the angle between the vectors \mathbf{p}_2 and \mathbf{p}_3 ,

$$\begin{aligned} E_1 &= M - E_2 - E_3, \\ M &= \sqrt{\mathbf{p}_2^2 + 2|\mathbf{p}_2||\mathbf{p}_3|\cos\theta_{23} + \mathbf{p}_3^2 + m_1^2} + \sqrt{|\mathbf{p}_2|^2 + m_2^2} + \sqrt{|\mathbf{p}_3|^2 + m_3^2}. \end{aligned} \tag{16}$$

In our approach Eq. (16) is used to calculate $\cos\theta_{23}$ and whenever the condition $|\cos\theta_{23}| \leq 1$ is satisfied the generated values of the energies and the angle itself are accepted. In this case, we rotate the plane spanned by the vectors \mathbf{p}_2 and \mathbf{p}_3 , together with the whole system, by a randomly chosen angle ϕ_{23} around the axis shown by the vector \mathbf{p}_3 . Next, with the help of two additional randomly generated Euler angles the orientation of the vector \mathbf{p}_3 is chosen. Finally, the system is boosted with the velocity of the parent particle. Obviously, the generated values of $|\mathbf{p}_1|$, $|\mathbf{p}_2|$, and $|\mathbf{p}_3|$ for which no solution of Eq. (16) exists are rejected.

Similarly to the two-body decays, the space-time origin of daughter particles is taken as the decay point of the parent. The daughters are automatically added to the list of particles in the event.

3.6 Storage of events

The particles are stored in the computer memory as collections corresponding to one event. Once the whole event is generated (all primordial particles are produced and all the unstable particles have sequentially decayed), the event is written out to the output file and is erased from the memory.

Each event in the output file consists of an event header (containing the number of particles in the event), and the particles themselves. Each particle is represented in a single line. It contains: the particle index for this event (useful for cross-referencing the decay parents and daughters), Particle Data Group identification number, PID, components of the momentum: p_x , p_y , p_z , energy E , mass, m (in GeV), space-time coordinates of creation: x , y , z , t (in 1/GeV), the parent index (-1 if the particle is primordial), finally, the decay flag (1 if particle has decayed, 0 if not). An example of the output file is shown in Fig. 13.

The format of the output file is a plain ASCII text, which is a standard used by many event generators. It has the advantage of having the complete information and being easily readable by the human or a computer program. It is, however, not efficient in terms of disk-space usage and data-access time. Therefore a simple ROOT macro `therm_tree.C` is provided, which converts the text output file into a ROOT `TTree`, which is stored in a ROOT file on disk. Events are divided into 500-event batches, each batch in a separate file.

The information stored in ROOT file differs slightly from the one stored in the text file; it does not contain the index. The position coordinates x , y , z , and t , are now converted to fm (we use $c=1$). Instead of the parent index and decay flag the `TTree` contains two PIDs. The first one, “fatherpid”, is the Particle Data Group PID of the immediate parent particle (or the PID of the particle itself, if it is primordial). The second, “rootpid”, is the PID of the original primordial particle, that is the particle at the beginning of the cascade decay tree. This enables us to distinguish between three scenarios: 1) the primordial particle has “pid” = “fatherpid” = “rootpid”, 2) the particle coming from the decay of primordial particle has “rootpid” = “fatherpid” and its own, different “pid”, and finally 3) the particle coming from a cascade decay has its own “pid”, a PID of its immediate parent – the

“fatherpid”, and the PID of the original primordial resonance – “rootpid”.

4 Programming structure of THERMINATOR

4.1 Technology and general design

THERMINATOR has been designed as an object-oriented program and has been written in the `c++` language. It also uses ROOT classes to store and manipulate its data structures.

The classes can be divided into three functional blocks. The first one deals with reading input files and storing the information in memory for the use by other classes. The second block takes care of storing the information of the generated particles and events. Finally, the third block contains the main logic of the program, as well as most of the mathematical formulas. It deals with the overall program execution control (including parsing the parameters), multiplicity calculation, particle generation, the decays, as well as storing the results.

4.2 Data storage block

The data storage functional block consists of several `c++` classes. The top-most is the ParticleDB, which stores pointers to information about all ParticleTypes and allows for easy searches by name or by number. It is filled with the data from the input files by the Parser class at the beginning of the `therm_events` program.

The basic object for storing the particle type data is the ParticleType class. It contains all the characteristics which are common to all the particles of the same type: the charge, baryon number, mass, width, name, *etc.* It also contains the pointer to the complete decay table of this particular particle type. There are as many instances of the ParticleType class as there are valid particle types read from the input file `particles.data`.

The DecayTable class is a collection of pointers to the specific decay channels. It deals consistently with the branching ratios. Its job is also to select a given decay channel, based on the random number that is passed to it.

The DecayChannel is a simple storage class, which contains the identifiers of the daughter particle types as well as the values of the branching ratios

for particular decay channels.

4.3 Calculation results storage block

This block of classes deals with storing the results generated by the `therm_events` program. It consists of two classes. The general one is the Event class. It stores pointers to the particles contained in the event. It is responsible for storing them sorted according to mass. It also manages the event generation process and holds the generated particle multiplicities for this specific event.

The Particle class stores information on each generated particle. There are as many instances of this class at any given moment, as there are particles in a current event. Each particle is defined by its particle type (which is a pointer to the corresponding instance of the ParticleType class) and characteristics that vary from particle to particle, that is the momentum \mathbf{p} , the creation point \mathbf{x} as well as information if it comes from a decay and if so, from which particle, and if it has decayed already. This class is also responsible for formatting the lines in the output file.

4.4 Main program block

This block contains the main acting classes of the `therm_events` program. One of them is the main program, which takes care of the command-line parsing, instantiating the ParticleDB classes, initiating reading of parameters and inputs, and running the appropriate generation and calculation routines.

The Integrator class contains the most important part of physics implementation of THERMINATOR. It includes the procedure which implements the Monte Carlo integrator of the emission functions. The integrator has three modes of operation: search for the maxima of distributions, straightforward integration (for multiplicity calculation), and generation of random numbers according to the probability density described by a given emission function. This latter procedure is the particle generation of THERMINATOR. All of these modes of operation are properly abstract and are not dependent on the particular emission function form. Thanks to this, the emission functions themselves can be relatively easily modified and new ones can be added with little effort.

One more helpful class included in the main program block is the ParticleDecayer. Its sole purpose is the implementation of the decay process. It assigns the pointer to the father particle. It is responsible for selecting

(by the Monte Carlo method) the decay channel, performing the necessary kinematic and space-time calculation (again using the Monte Carlo procedures wherever it is appropriate, *e.g.*, in generating randomly the directed decay axis). Finally it returns pointers to the newly created Particle class instances containing the daughter particles. Both 2-body and 3-body decays are implemented in ParticleDecayer.

5 Testing against existing calculations

During the development of THERMINATOR, special care was taken to ensure that the obtained results are in perfect agreement with those delivered by the MathSHARE package [53]. The most sensitive test available was to check the shape of the p_T -spectra of many different particle species. Since THERMINATOR is based on Monte Carlo methods, the agreement could only be judged within the uncertainties of such method, which are decreasing with the increase in the number of generated events.

The agreement at the input level was ensured by simply using exactly the same files `particle.data` and `decays.data` as input to THERMINATOR and MathSHARE. In this way, the same number and types of particles were used, as well as the same decay channels and branching ratios. The tests were done in two steps. First, the p_T -distributions of primordial particles were compared. The results of this comparison are seen in Fig. 3. For all considered particle types, the results of quasi-analytic calculations done in MathSHARE and histograms obtained with the help of THERMINATOR agree within the error expected from the Monte Carlo procedure. The second test was the analysis of the p_T -spectra, but this time with full resonance contribution included. The results for this test can be seen in Fig. 4. Again, the agreement reached with a sample of 1000 events is impressive, proving that not only the initialization procedures but also the decay procedures yield identical results.

6 Yielding new results

This Section contains examples of the physical results obtained with the help of THERMINATOR. More results and details focusing on physics will be presented in future publications. All the simulations were done with the

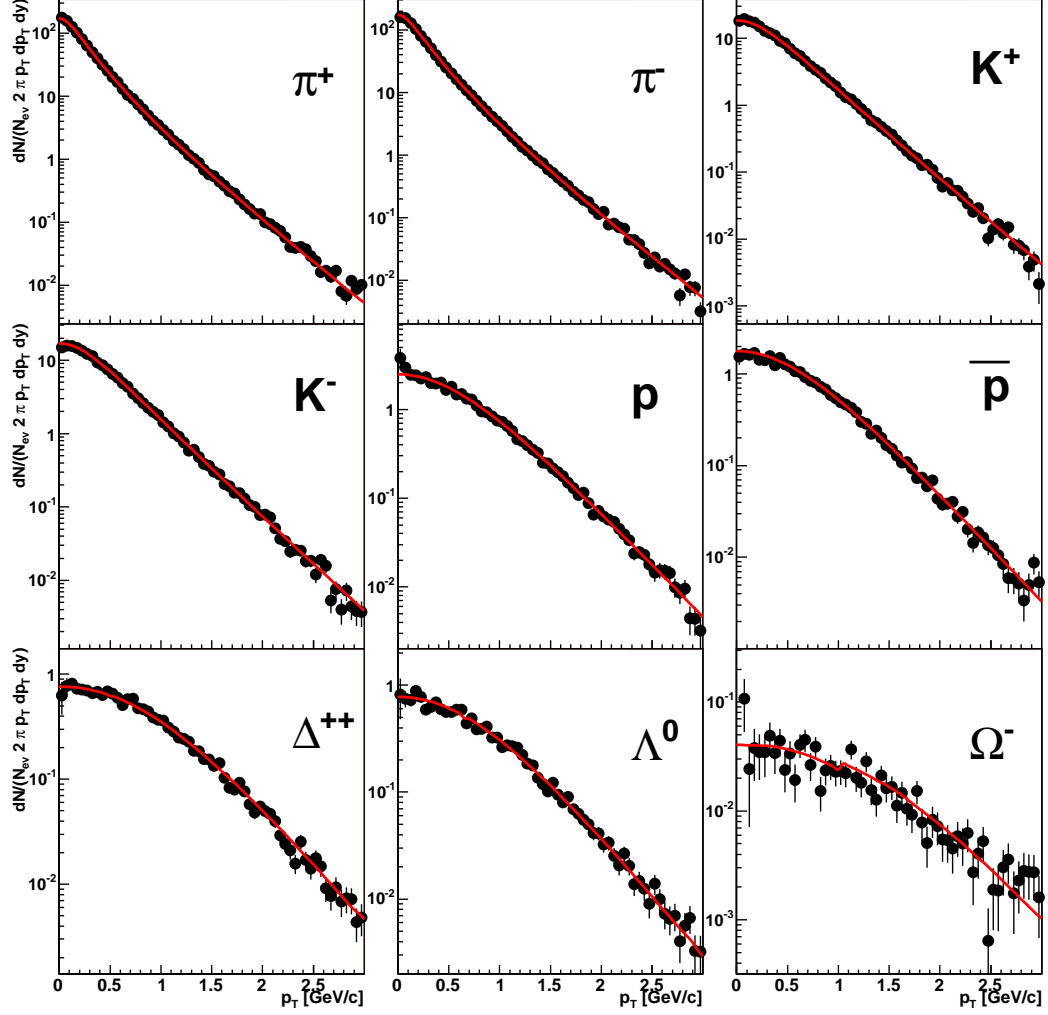


Figure 3: Comparison of the p_T spectra of primordial particles obtained from **THERMINATOR** (circles) and **MathSHARE** [53] (lines) for the Cracow single-freeze-out model. The model parameters corresponding to the best fit to the most central PHENIX data for Au + Au @ 200 GeV are taken from Ref. [54]. The sample contains 1000 events. The errors on the **THERMINATOR** results are statistical. A perfect agreement of the two independent codes is observed.

parameters taken from Ref. [54], which were obtained by fitting the STAR experiment data with the **MathSHARE** package. These parameters are included

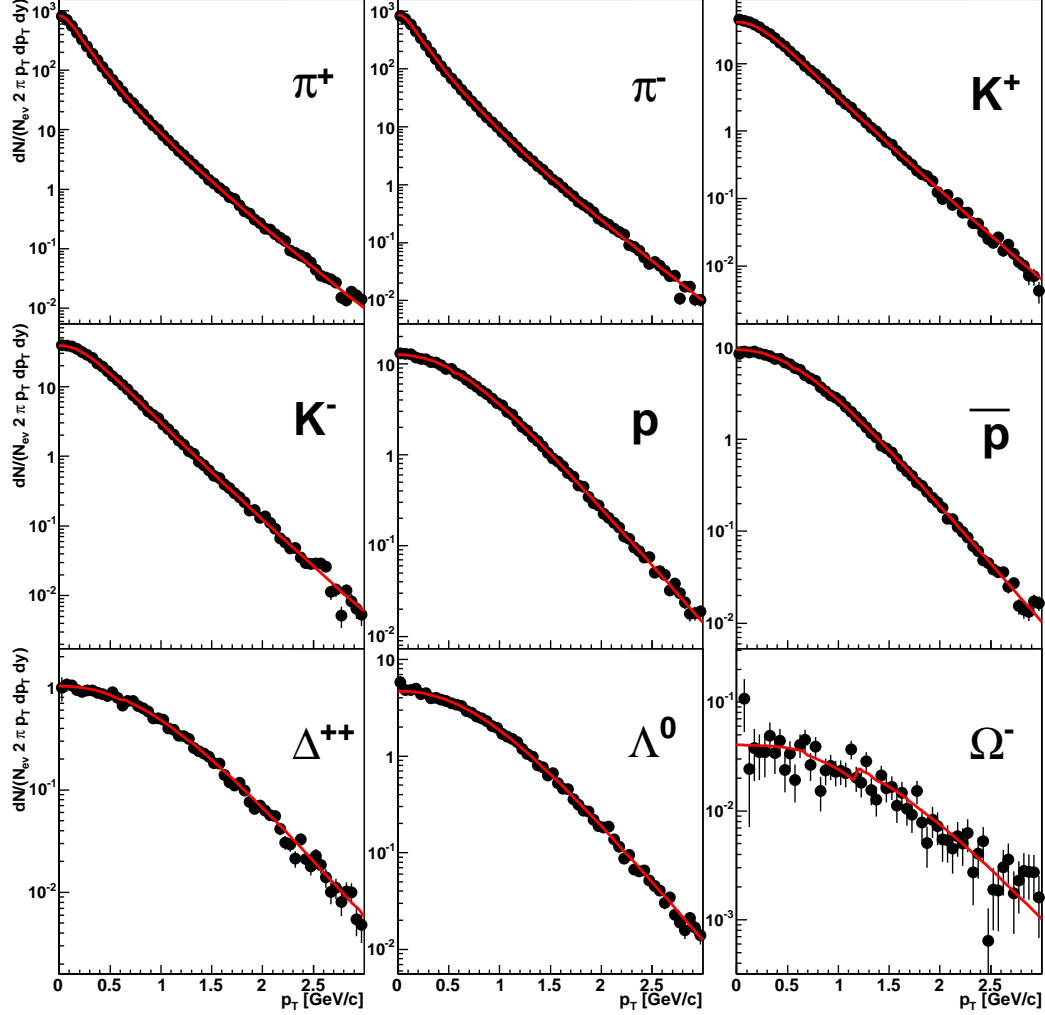


Figure 4: Same as Fig. 3 for the final (primordial + products of decays) distributions. A perfect agreement of the two independent codes is visible.

as default in the input file `therminator.in`. The generated sample used here contains 500 events.

In Figs. 5 and 6 we show the p_T -spectra of various particle species. Such spectra were first reported in the original papers on the single-freeze-out model [16, 43]. The user may generate his own spectra for any desired particle by means of simply modifying the attached ROOT scripts `figure5.C`

or figure6.C.

Figure 7 shows the rapidity distributions of pions, kaons, and protons in the midrapidity region. One may observe the boost-invariance imposed on the model. With relatively simple modifications the program may be used to describe realistic rapidity distribution in the full rapidity range, such as for example in Ref. [49].

THERMINATOR allows for deeper understanding of the physical results, in particular of the role played by the resonances. As an example in Fig. 8 we present the anatomy of the π^+ transverse momentum spectra. One can see that the contribution from the resonances is dominant, with only one quarter of all pions being primordial. The resonance effect is important in the whole displayed p_T range. One can also see that, as expected from the kinematics, the contribution from the three-body decay of the omega meson has a steeper distribution than the contributions from two-body decays. Analogous anatomy of the proton p_T spectra is presented in Fig. 9.

Further plots show some very interesting and novel observables which were not accessible from previous programs implementing the model. These

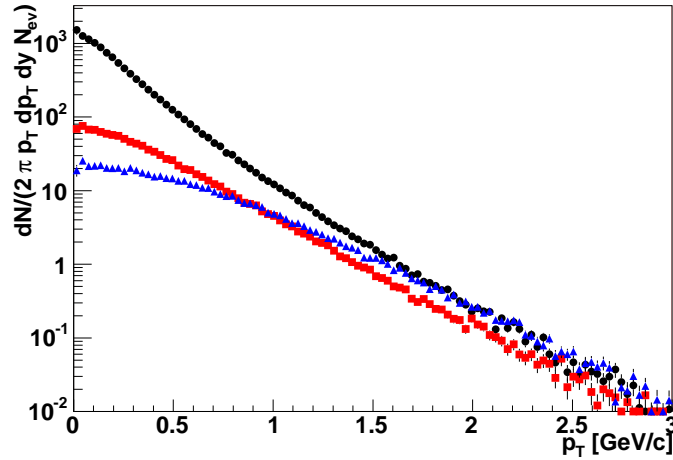


Figure 5: The p_T spectra of pions (circles), kaons (squares) and protons (triangles) generated from **THERMINATOR** for the Cracow single-freeze-out model with default parameters from `therminator.in`. The sample contains 500 events. The errors are statistical. The figure is generated by the ROOT script figure5.C.

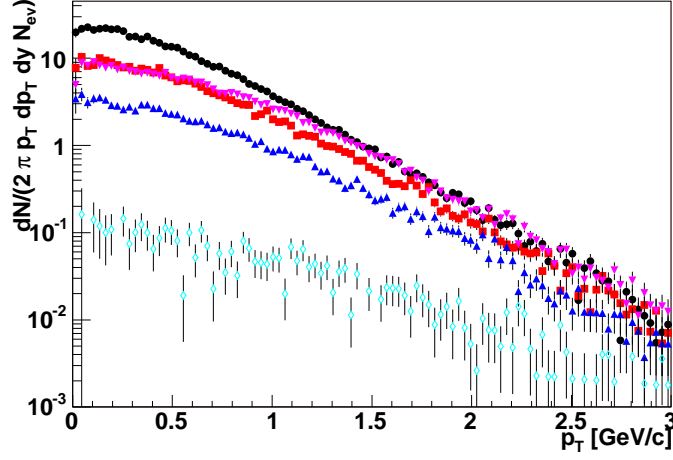


Figure 6: The p_T spectra of ρ mesons (filled circles), K_0^* mesons (squares), ϕ mesons (up-triangles), Λ^0 barions (down-triangles), and Ω^- barions (diamonds) generated from THERMINATOR for the Cracow single-freeze-out model with default parameters from `therminator.in`. The sample contains 500 events. The errors are statistical. The figure is generated by the ROOT script `figure6.C`.

observables refer to the space-time picture of particle production in relativistic heavy-ion collisions. For instance, in Fig. 10 we show the distribution of the space and time coordinates of the emission points of pions. For the primordial particles the emission point is the point on the freeze-out hypersurface, while for particles coming from resonances the emission point is simply the point where the decay occurs. The top-left panel shows the distribution of the transverse coordinates of the pion emission points, r_T . The primordial pions are denoted by squares, the pions from the ρ meson by up-triangles, and the pions from the ω meson by down-triangles. The dots indicate the full yield (from *all* resonances). For r_T in the range from zero to $\rho_{\max} = 7.74$ fm (the maximum transverse size of the freeze-out hypersurface) the observed distributions are flat, reflecting the uniform distributions of the primordial particles. For larger values of r_T we can see the tails generated by the decays of the resonances. Resonances with longer lifetime generate longer tails. This is clearly seen in the top-right panel, where the logarithmic vertical scale is used. One can also observe that the contribution from the

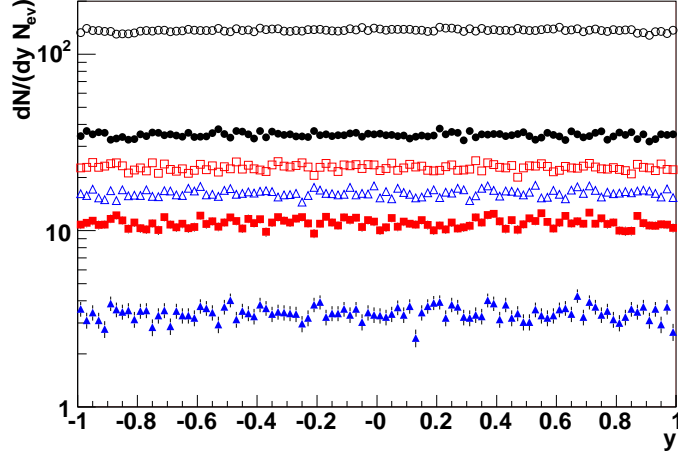


Figure 7: The rapidity distributions of pions (circles), kaons (squares) and protons (triangles) generated from **THERMINATOR** with the default input file. The closed symbols show the rapidity distribution of primordial particles. The open symbols show the distributions of the final particles. The sample contains 500 events. The boost-invariance assumed in the present model is clearly seen. The figure is generated by the ROOT script `figure7.C`.

long living ω meson saturates the full contribution at $r_T > 20$ fm.

The two lower panels of Fig. 10 show the analogous analysis with regard to the emission time t . The emission starts at $t = \tau = 9.74$ fm and peaks around $t = 14$ fm. This reflects the geometry of the freeze-out hypersurface assumed in the Cracow model, Eq. (9), as well as the finite lifetime of the resonances.

THERMINATOR may be used to analyze various correlations. As an example, Fig. 11 shows the space-momentum correlation encountered in relativistic heavy-ion collisions. One can see that the x -coordinate of the pion emission point is correlated with the x -coordinate of its momentum. This is a characteristic feature of the systems exhibiting the transverse flow.

The plots shown in this paper are only a few examples of the variety of physical results that can be obtained with **THERMINATOR**. Many novel analyses may be performed, including a detailed study of the resonance decay contribution to particle spectra, a comprehensive study of two-particle correlations, such as the HBT correlations of pions, kaons, and protons. One

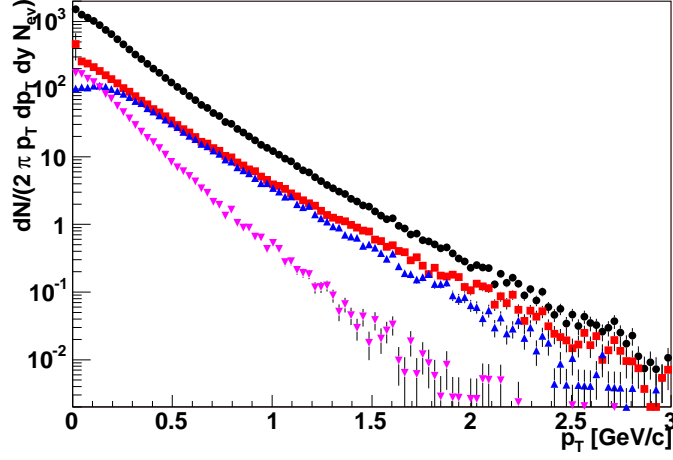


Figure 8: The anatomy of resonance contribution to the π^+ transverse-momentum spectra. The plot shows absolute contribution to the overall π^+ spectra (circles) from: primordial pions (squares), pions from the ρ^0 and ρ^+ decays (up-triangles), and pions from the ω decays (down-triangles). The sample contains 500 events. The figure is generated by the ROOT script `figure8.C`.

may investigate also the correlations of non-identical particles, this way getting the information about relative distances between their emission points. All such tasks may be achieved with a complete inclusion of resonance decays.

An extension of the freeze-out geometry of the model to a cylindrically non-symmetric case, such as emerging in non-central collisions, would allow for studies of the elliptic flow. As already mentioned, an analogous extension to boost non-invariant geometry would prepare ground for studies of the dependence of observables on the rapidity variable y . Such extensions are planned by the authors in the future.

7 Installation

THERMINATOR is distributed in a form of a `.tar.gz` archive containing the `c++` source and the data files. Running under ROOT ver. 4.0x and compiler gcc 3.x has been tested. In order to run THERMINATOR one needs:

- `c++` compiler

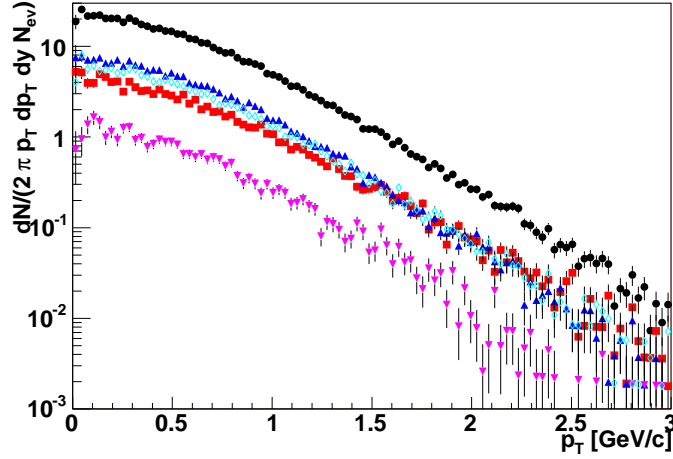


Figure 9: The anatomy of resonance contribution to the proton p_T spectra. The plot shows absolute contribution to the overall proton spectra (closed circles) from: primordial protons (squares), protons from the Λ^0 decays (up-triangles), protons from the Σ hyperon decays (down-triangles), and protons from the Δ resonance decays (open circles). The sample contains 500 events. The figure is generated by the ROOT script `figure9.C`.

- ROOT libraries and include files

After unpacking the .tar.gz archive in a separate directory, one compiles THERMINATOR by issuing the `make` command in this directory. The executable of THERMINATOR - `therm_events` is created in the same directory, as well as the `therm_tree` converting program. The SHARE input files are placed in the `share` subdirectory.

8 Organization of the c++ package

8.1 Directory tree

source code (main directory):

`therm_events.cxx` – main program

`ParticleDB.cxx`, `ParticleDB.h` – `ParticleDB` class

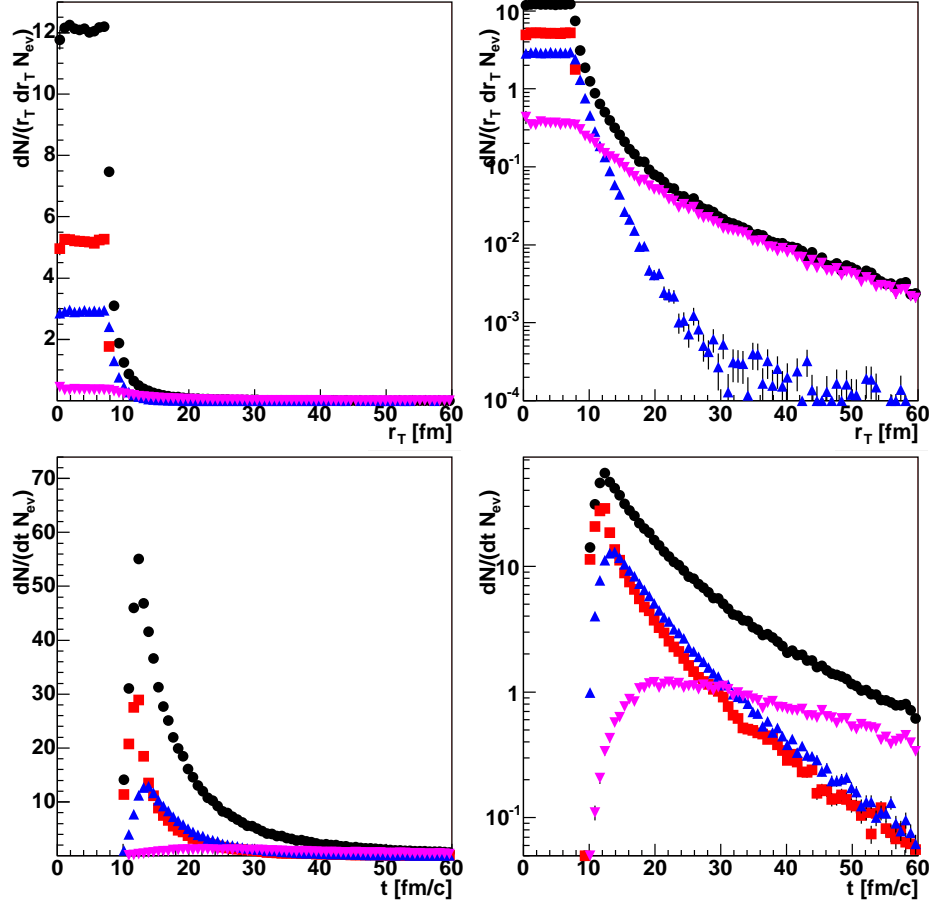


Figure 10: Space-time picture of the π^+ emission process. The plots in the upper row show spatial distribution of the pion emission points, $dN/(r_T dr_T)$. The symbol r_T denotes the transverse radial coordinate of the points where the pions are born. The lower plots show the distribution of the pion emission times. Plots on the left are with linear vertical scale, plots on the right are copies with the logarithmic scale. The plots show absolute contribution to the overall distributions (circles) from the primordial pions (squares), the pions from the ρ^0 and ρ^+ decays (up-triangles), and the pions from the ω decays (down-triangles). The sample contains 500 events. The figure is generated by the ROOT script `figure10.eps`, see the text for more details.

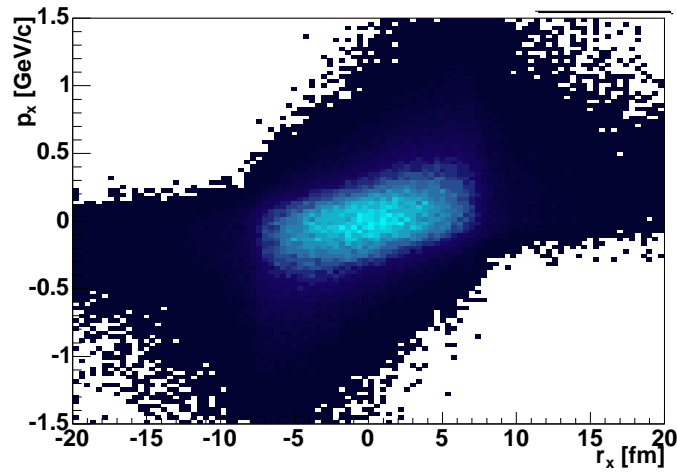


Figure 11: The space-momentum correlation in THERMINATOR. The plot shows the correlation between spatial and momentum x-coordinate for the pions. The sample contains 500 events. The figure is generated by the ROOT script `figure11.eps`

`ParticleType.cxx`, `ParticleType.h` – `ParticleType` class
`ReadPar.cxx`, `ReadPar.h` – `ReadPar` class
`Particle.cxx`, `Particle.h` – `Particle` class
`DecayTable.cxx`, `DecayTable.h` – `DecayTable` class
`DecayChannel.cxx`, `DecayChannel.h` – `DecayChannel` class
`Event.cxx`, `Event.h` – `Event` class
`ParticleDecayer.cxx`, `ParticleDecayer.h` – `ParticleDecayer` class
`Integrator.cxx`, `Integrator.h` – `Integrator` class
`Parser.cxx`, `Parser.h` – `Parser` class
`THGlobal.h` – global helper definitions
`Makefile` – The makefile

`therm_tree.C` – source of the text-to-TTree conversion macro

Data files (share subdirectory):

`particles.data` – Particle data file

`decays.data` – Particle decays data file

Input files (main directory):

`therminator.in` – Default input data file

9 How to run THERMINATOR

It is assumed that THERMINATOR has been successfully compiled and the `therm_events` executable is in the user's search path. The user must also know the location of the SHARE input files `particles.data` and `decays.data`.

9.1 Instructions for the user

First, the user must examine/edit the `therminator.in` file. If the name of the file is changed, it then must be supplied as a command-line parameter to the `therm_events` program. The meaning of the various parameters is described in section 3.2. The input file is also conveniently commented and contains reasonable default values. A default input file is Fig. 12. Providing the input file is in the current directory, one can issue the command:

```
therm_events
```

This runs the program, which generates the maximum integrand values, the average multiplicities, and the events themselves. As a result a text output file with the default name `event.out` is created. Then the user can issue the command

```
therm_tree
```

and the output file is converted into the ROOT TFile `event1.root` containing the TTree named `particles`. If the user changes the name of the output file from `therm_events` to `<name>.out`, he must supply this name to `therm_tree` as a command-line parameter. The output file from `therm_tree` will then be called `<name>1.root`.

In case where more than 500 events are requested, the output ROOT files are divided into `n` batches of maximum 500 events, with the names `<name>n.root`.

9.2 Sample run

This sample run assumes that the user is in a directory where the default `therminator.in` file shown in Fig. 12 is located and that the `SHARE` input files are in the `share` subdirectory. After issuing the `therm_events` and `therm_tree` commands the directory should contain the `event.out` ascii output file as well as the `event1.root` output file. The format of the `event.out` file is explained in Fig. 13.

10 Analysis with ROOT

The great advantage of the organization of `THERMINATOR` is the compliance to the ROOT standard. Having the `event1.root` file, it is possible to browse the event tree and generate physical results, even the involved ones, in a very simple manner. It is assumed that the user knows at least the basics of ROOT.

The user can start a ROOT interactive session:

```
root event1.root
```

and produce some simple plots from the ROOT command line. For example, a plot similar to the squares plot of Fig. 5 can be obtained with the command (typed in one line) such as

```
particles->Draw("sqrt(px*px+py*py)", "(1.0/sqrt(px*px+py*py))*  
(pid==211&&fatherpid==211&&abs(0.5*log((e+pz)/(e-pz)))<0.5)")
```

The contribution from the omega resonance (PDG PID = 223) to the pion m_T -spectra can be viewed with a different command,

```
particles->Draw("sqrt(mass*mass+px*px+py*py)",  
"(1.0/sqrt(mass*mass+px*px+py*py))*  
(pid==211&&fatherpid==223&&abs(0.5*log((e+pz)/(e-pz)))<0.5)")
```

The correlation between particle's momentum and position (as seen in Fig. 11) can be obtained with


```
particles->Draw("px:x>>hxpx(100,-20,20,100,-1.5,1.5)",
"pid==211&&abs(0.5*log((e+pz)/(e-pz)))<0.5")
```

The particle identification numbers, useful in this interactive analysis, can be read from the `particles.data` file.

More elaborated examples, in particular the macros used to generate the figures of this paper (`figure5.C`, *etc.*) are included in the `THERMINATOR` distribution. To use data from more than one `eventn.root` file at the same time, use the `Add` method of the `ROOT TChain` class several times. An example of the method usage is shown in the figure macros.

11 Conclusion

We hope that `THERMINATOR` will become a versatile tool allowing for a simple implementation of the thermal approach in analyses of heavy-ion experiments. It may be useful for theorists exploring their ideas, as well as experimentalists searching for simple and working models which can be confronted to the data. The results of the code can be directly interfaced to `ROOT – An Object-Oriented Data Analysis Framework`. This way, `THERMINATOR` becomes fully compatible with the basic modern software tool of particle physics.

New possibilities offered by the program were illustrated in Sec. 6. The big advantage offered by `THERMINATOR` is the possibility of exploring the space-time evolution of the particle system formed in relativistic heavy-ion collisions. This allows for many interesting physics studies which should be carried out in the future, such as exploration of various freeze-out surfaces, calculation of the HBT correlations with full treatment of resonance decays, analysis of the freeze-out criteria, investigation of the role of resonances, calculation of balance functions in various variables, analysis of correlations of non-identical particles, *etc.* Future extensions of the code should incorporate automatic fitting procedures of the model parameters to various observables, such as the transverse-momentum spectra or HBT radii. Also, the straightforward extension to cylindrically non-symmetric and boost non-invariant geometries is planned, which would allow for further interesting studies.

Acknowledgments

We thank Jan Pluta for his helpful comments and continuous encouragement expressed during the realization of this project.

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```

### This is the Therminator input file ###
# Therminator behaviour is controlled through this file
# Please fill in all the necessary values

# Number of events to generate
NumberOfEvents = 500

# Start each event with a new random seed taken from current time
Randomize = 1

# The type of input tables
# Now available:
# SHARE - input files from SHARE
TableType = SHARE

# Specify in which directory the SHARE input files are
InputDirSHARE = ./share

# Name of the file to store the events in
EventOutputFile = event.out

# The model of freeze-out to use
# Now available:
# SingleFreezeOut
# BlastWaveVT
FreezeOutModel = SingleFreezeOut

# Values of parameters of the BlastWave model
# used only when this FreezeOutModel is selected
# Flow velocity
BWVt = 0.55

# Parameters common to both models
# proper time at freeze-out [fm]
Tau = 9.74
# maximum transverse radius [fm]
RhoMax = 7.74
# Temperature [GeV]
Temperature = 0.1656
# Chemical potentials for Isospin, Strangeness, Baryon [GeV]
MiuI = -0.0009
MiuS = 0.0069
MiuB = 0.0285

# Ranges of integration for z-variables
AlphaRange = 8.0
RapidityRange = 4.0

# Number of samples used in multiplicity and max. integrand determination
NumberOfIntegrateSamples = 1000000

```

Figure 12: An example (default) input parameter file `therminator.in`

Therminator text output																			
all_particles_p_x																			
Therminator																			
1	11310	0.000	0.000																
1	-9300	-5.606520e-01	-6.202420e-02	-4.821753e+00	5.424378e+00	2.420000e+00	-3.179843e+01	-6.773356e+00	-1.711961e+02	1.811342e+02	-1	1							
2	9300	5.972534e-01	9.567281e-01	-5.015253e+00	5.681655e+00	2.420000e+00	8.483843e+00	1.632971e+01	-9.527784e+01	1.089081e+02	-1	1							
3	40225	-4.558259e-01	1.638407e+00	-4.854391e+00	5.650503e+00	2.339000e+00	-2.548801e+00	2.970237e+01	-9.342735e+01	1.098266e+02	-1	1							
4	5128	-8.738711e-01	-7.882234e-01	-5.668153e+00	6.210910e+00	2.250000e+00	-1.069163e+01	-2.592587e+01	-1.248685e+02	1.371972e+02	-1	1							
5	4128	2.732464e-01	-1.444380e+00	-6.337567e+00	6.883905e+00	2.250000e+00	1.158048e+01	-3.077940e+01	-1.223908e+02	1.360347e+02	-1	1							
6	3218	-5.843346e-01	1.045702e+00	-5.346095e+00	5.911351e+00	2.220000e+00	-2.950714e+01	2.158621e+01	-7.053663e+01	9.357631e+01	-1	1							
7	2128	-9.628190e-01	-4.519428e-01	3.557912e+00	4.311161e+00	2.190000e+00	-2.314206e+01	1.485339e+01	3.668721e+01	6.742851e+01	-1	1							
8	-1218	1.922882e+00	5.978578e-01	-2.469414e-01	2.985296e+00	2.190000e+00	3.031767e+01	9.619324e+00	-1.762363e+01	6.137393e+01	-1	1							
9	319	-9.148169e-02	3.549711e+00	9.887226e+00	1.070271e+01	2.045000e+00	-1.242922e+01	2.574922e+01	1.025089e+02	1.173459e+02	-1	0							
10	229	7.078858e-01	-4.458794e-01	-2.787678e-01	2.216930e+00	2.034000e+00	3.885054e+00	-1.311497e+01	-8.993361e+00	5.208119e+01	-1	0							
11	229	-1.552147e-01	-6.102028e-01	-1.610166e+00	2.669500e+00	2.034000e+00	1.001138e+01	-1.723043e+01	-3.303138e+01	6.271094e+01	-1	0							
12	3118	5.620824e-01	2.138908e+00	7.525494e-01	3.094850e+00	2.030000e+00	9.812499e+00	1.146698e+01	-2.627588e+00	5.176055e+01	-1	1							
13	3218	-9.211756e-01	-3.007009e-01	2.683836e+00	3.501837e+00	2.030000e+00	-1.353343e+01	1.283712e+01	6.510273e+01	8.384977e+01	-1	1							
14	-8901	-1.955413e+00	1.739135e+00	4.604367e+00	5.670131e+00	2.025000e+00	-1.451838e+01	2.669975e+01	6.143839e+01	8.451515e+01	-1	1							
15	8901	-1.054209e+00	1.208663e+00	2.556273e+00	3.634196e+00	2.025000e+00	-1.675454e+01	-1.373259e+00	6.386806e+01	8.249972e+01	-1	1							
16	219	5.184602e-01	2.878743e-01	3.522405e+00	4.100635e+00	2.014000e+00	2.526679e+01	1.565849e+01	8.922485e+01	1.062504e+02	-1	1							
17	119	1.181179e+00	9.084622e-02	3.740515e+00	4.410339e+00	2.014000e+00	1.286691e+01	1.545997e+01	8.261133e+01	9.835483e+01	-1	1							
18	119	-4.442523e-01	-6.671208e-01	4.370206e+00	4.878248e+00	2.014000e+00	-1.083269e+01	-1.241051e+01	1.271948e+02	1.374568e+02	-1	1							
19	4231	6.382718e-01	-1.607474e-01	-6.128849e-01	2.202035e+00	2.010000e+00	9.537997e+00	-4.214772e+00	-1.132449e+01	5.178278e+01	-1	0							
20	2118	1.449930e+00	-5.741769e-02	-8.508298e+00	8.848685e+00	1.950000e+00	3.166713e+01	1.122480e+01	-2.342800e+02	2.417858e+02	-1	1							
21	67000	-1.050218e+00	-9.938995e-01	2.305767e+00	3.348112e+00	1.950000e+00	-1.928524e+01	-2.272793e+01	8.856042e+01	1.057161e+02	-1	1							
22	-67001	7.715302e-02	1.037076e+00	4.093344e+00	4.651821e+00	1.950000e+00	6.928140e+00	3.136835e+01	1.511296e+02	1.622240e+02	-1	1							
23	67001	-2.715839e+00	-7.832633e-01	2.378036e+00	4.176941e+00	1.950000e+00	-1.507388e+00	-9.132637e+00	5.528433e+01	7.474295e+01	-1	1							
24	-2118	2.414304e+00	-1.524237e+00	3.043907e-01	3.470924e+00	1.950000e+00	2.302119e+01	-6.608043e+00	4.609110e+00	5.513039e+01	-1	1							
25	-1118	-9.890418e-02	-8.215015e-01	-1.080623e+00	2.378002e+00	1.950000e+00	-3.149344e+01	-8.522650e+00	-8.271713e+00	5.981110e+01	-1	1							
26	23114	5.574685e-01	5.428459e-01	-8.426241e-01	2.253679e+00	1.940000e+00	1.237696e+01	9.430638e+00	-2.014642e+01	5.561006e+01	-1	1							
27	23214	7.012713e-01	2.622612e-02	-5.11965e+00	4.961303e+00	1.940000e+00	2.710685e+01	-1.899049e+01	-1.117306e+02	1.265844e+02	-1	1							
28	23214	-1.636995e+00	8.970330e-01	1.248185e+00	2.967488e+00	1.940000e+00	-2.778232e+01	2.590974e+01	2.348154e+01	6.662604e+01	-1	1							
29	11116	-4.907981e-02	6.029544e-01	4.021908e+00	4.501845e+00	1.930000e+00	-2.079292e+01	1.505045e+00	1.316500e+02	1.421647e+02	-1	1							
30	11116	8.883509e-01	3.861457e-01	5.421343e-01	2.226451e+00	1.930000e+00	3.472230e+01	1.833360e+00	-7.198091e+00	6.087106e+01	-1	1							
31	11116	-7.480544e-02	-3.928761e-01	2.530815e+00	3.207783e+00	1.930000e+00	1.302792e+01	-1.600607e+01	7.222514e+01	8.992701e+01	-1	1							
32	-12126	-6.811600e-01	1.125209e+00	5.594173e+00	6.062157e+00	1.930000e+00	-1.811596e+01	1.119626e+01	1.101402e+02	1.225923e+02	-1	1							
33	-11116	3.802464e-02	-2.691408e+00	-9.004810e+00	9.594615e+00	1.930000e+00	1.633592e+01	-2.806330e+01	-1.099985e+02	1.248942e+02	-1	1							
34	-22214	8.292163e-02	5.497412e-01	2.990627e+00	3.597130e+00	1.920000e+00	1.733447e+01	6.755888e+00	2.010524e+01	5.652274e+01	-1	1							
35	-21114	3.299353e-01	6.339179e-01	4.201018e+00	4.673935e+00	1.920000e+00	8.914739e+00	3.016360e+01	1.732359e+02	1.828783e+02	-1	1							
36	-21114	-1.138183e+00	-1.512093e+00	2.400448e-01	2.706641e+00	1.920000e+00	-1.857358e+01	-3.195330e+01	1.180073e+01	6.284682e+01	-1	1							
37	-13216	5.246929e-01	1.970800e-01	-4.127102e+00	4.584140e+00	1.915000e+00	2.866244e+01	1.635630e+00	-1.081820e+02	1.223602e+02	-1	1							
38	13226	-1.522511e-01	-2.420183e-02	1.352760e+00	2.349671e+00	1.915000e+00	9.019017e+00	-2.306061e+01	1.999257e+01	5.879891e+01	-1	1							
39	13216	-3.865036e-01	4.961109e-01	-2.481840e+00	3.197228e+00	1.915000e+00	7.351436e-01	-1.103777e+01	-5.435493e+01	7.430549e+01	-1	1							
40	-13116	1.386959e-01	1.545150e+00	6.135968e+00	6.612416e+00	1.915000e+00	1.306130e+01	2.065295e+01	1.243332e+02	1.360160e+02	-1	1							
41	-13116	-3.747976e-01	8.902073e-01	-6.935374e+00	7.259448e+00	1.915000e+00	-9.452444e+00	2.785301e+01	-1.679386e+02	1.775190e+02	-1	1							
42	-22222	-1.103887e+00	3.696479e-01	-3.788353e+00	4.399423e+00	1.910000e+00	-1.440330e+01	1.936447e+01	-8.564384e+01	1.017928e+02	-1	1							
43	-22222	-1.180230e+00	-2.232448e+00	4.897472e+00	5.831818e+00	1.910000e+00	-8.271525e+00	-3.324342e+01	4.432265e+01	7.471623e+01	-1	1							
44	22122	-1.390629e+00	5.130754e-01	-5.086694e+00	5.632020e+00	1.910000e+00	-2.859103e+01	2.660733e+00	-1.968870e+02	2.050207e+02	-1	1							
45	22122	1.354408e+00	-3.782093e-01	2.89813e+00	3.296787e+00	1.910000e+00	2.538957e+01	1.541365e+01	6.771431e+01	8.894893e+01	-1	1							
46	-21212	-2.960950e+00	-9.416599e-01	2.191330e+00	4.254876e+00	1.910000e+00	-3.782261e+01	2.021553e+00	4.944666e+01	7.952411e+01	-1	1							
47	11116	1.928480e-02	1.591572e-01	-7.169393e-01	2.041747e+00	1.905000e+00	1.659802e+01	6.268038e+00	-8.658268e+00	5.323742e+01	-1	1							
48	1216	1.118424e+00	-1.135706e-01	2.306400e+00	3.266540e+00	1.905000e+00	2.523493e+01	7.337104e+00	1.130757e+02	1.261794e+02	-1	1							
49	-2126	1.386378e-01	3.051965e-02	-9.013189e-02	1.912407e+00	1.905000e+00	1.080873e+01	-1.476715e+01	-5.944547e+00	5.305383e+01	-1	1							
50	2126	-7.534297e-01	-6.843172e-01	-1.020784e+00	2.388927e+00	1.905000e+00	-2.628962e+01	9.069409e+00	-4.488392e+01	7.233560e+01	-1	1							
51	-1216	-2.113514e+00	3.874093e-01	2.438567e-01	1.970811e+00	1.905000e+00	7.212613e+00	2.806810e+01	3.110289e+00	5.739416e+01	-1	1							
52	2226	2.417437e-01	7.920690e-01	-5.005760e+00	5.419638e+00	1.905000e+00	-2.589058e+01	1.188671e+01	-2.107487e+02	2.183371e+02	-1	1							
53	2226	1.850948e+00	6.405938e-01	-4.723289e-01	2.772812e+00	1.905000e+00	3.097078e+01	-1.404472e+00	-3.773492e+01	6.949504e+01	-1	1							
54	23124	-5.010354e-01	-1.086540e-01	-3.165771e+00	3.722506e+00	1.890000e+00	-1.743995e+01	-2.130646e+01	-5.174672e+01	7.668321e+01	-1	1							
55	23124	-1.354372e+00	6.543934e-01	-3.518323e-01	2.440992e+00	1.890000e+00	-2.355396e+01	4.446426e+00	-3.900592e+01	6.738320e+01	-1	1							
56	1233	7.424609e-01	-3.788798e-01	-4.674570e+00	5.103008e+00	1.869300e+00	1.955484e+01	-1.676271e+01	-1.860192e+02	1.941932e+02	-1	0							
57	1233	-2.862624e-02	-2.604978e+00	3.742119e+00	4.927927e+00	1.869300e+00	-9.344057e+00	-2.180831e+01	1.003416e+02	1.434966e+02	-1	0							
58	337	7.587479e-01	-1.497535e+00	-1.447492e+00	2.889785e+00	1.854000e+00	1.553033e+01	-3.050430e+01	-1.468059e+02	6.190070e+01	-1	1							
59	337	5.963221e-01	4.532649e-01	5.740089e+00	6.078403e+00	1.854000e+00	6.991626e+00	-3.081487e+00	2.296486e+02	2.350347e+02	-1	1							
60	337	8.631210e-01	9.815413e-02	8.986448e-02	2.049391e+00	1.854000e+00	3.620038e+01	-1.505132e+01	-2										